COMPENSATED PULSED ALTERNATORS TO POWER ELECTROMAGNETIC RAILGUNS

William C. McCorkle
U.S. Army Aviation & Missile Command, ATTN: AMSAM-RD
Redstone Arsenal, AL 35898

Abstract

Electric armaments of coilgun or railgun types require repeated bursts of extremely high power (gigawatts), considerable amounts of energy (tens of megajoules), delivered in several milliseconds.

Compensated pulsed alternators, due to their high power and energy densities, have emerged as leading candidates for power supplies for railguns of the future.

This paper examines test results of completed compulsator-based systems such as the "Cannon Caliber Electromagnetic Launcher," with the objective of formulating estimates of upper bounds to the delivered energy density achievable by rotating electrical machines designed to meet the power requirements of electromagnetic guns. The effects of increasing rotational speeds (for increased energy storage and higher voltage) and of increasing allowable composite material strength and temperature levels on armature-excitation mutual inductances is considered in scaling up machines for application to tank main armament requirements.

I. INTRODUCTION

A. Background

Under the direction of the Army Research Laboratory (ARL) (and earlier a number of other organizations, including DARPA), pulsed power generator research on machines known as compensated pulsed alternators ("compulsators") has been performed at the Institute for Advanced Technology and the Center for Electromagnetics at the University of Texas at Austin (IAT/CEM) for many years. Compulsators are characterized by use of aluminum conductors, high strength composites, self-excitation and non-magnetic materials in "air-core" designs. Compensation refers to special techniques to reduce machine internal impedance. This work has been well documented [1,3,4,5,12] in papers published in these Transactions (with an exception noted below).

Two single-pole-passage compulsators were designed and fabricated during the first phase of this work [1]. A large machine, the 9 MJ Range Gun System [3], was virtually completed [12] but never tested. The Cannon Caliber Electromagnetic Launcher (CCEML), intended to demonstrate a multi-shot capability, was to be through testing in Jan 1990 [1]. The final design was documented in 1994 [3] and the testing completed in 1996 [5].

The CCEML demonstrated a single shot launch package (LP) energy of .279 MJ, 89% of the goal in spite of fabrication problems which limited the rotor to about 70% of the design speed of 12000 rpm. Based on total compulsator weight, this represented a breech delivered energy density (DED), the preferred metric, of about 0.085 J/g. Because of the rotor speed limit, the multi-shot capability was never demonstrated.

The second phase of the work, known as the Focused Technology Program (FTP), has been devoted to multiple-pole-passage, multi-phase designs which offer greater flexibility in pulse length and shape as well as much higher machine speeds. The first machine of this genre, the Subscale FTP (SSFTP), has been tested at the design speed of 12000 rpm, discharging into a non-optimal 3-meter railgun.

The FTP efforts have not yet been published, but the author has obtained test results through ARL[9]. SSFTP results are generally in agreement with predictions from detailed mathematical modeling [8]. The SSFTP is about 300 kg lighter than the CCEML, and produced about 0.36 MJ in the LP, for a muzzle specific energy of 0.12 J/g compared with 0.085 J/g for the CCEML, and breech specific energy of 0.56 J/g vs. 0.17 J/g for the CCEML.

The established DED goal for a tank main armament system is 10 J/g, (not counting the gun or drive motor weights).There are a number of reasons why the CCEML and SSFTP DED values are so far from those required for a tank armament application, including being designed to very modest goals. Nevertheless, their performance, utilizing most of the features and techniques mentioned above and intended to enable reaching tank gun performance levels, certainly raises the question of feasibility to reach the 10 J/g goal with rotating machine technology. This paper addresses this question.

For a tank main armament-sized FTP design, the input to the railgun must be about 40 MJ or more of electrical energy. The compulsator must convert 40+ MJ of kinetic energy into electrical energy (some of which is recoverable). A stored kinetic energy capacity of 200-300 MJ is required to allow several shots before "remotoring" back up to speed. Other constraints, imposed by ARL based on suitability for a Future Combat Vechile (FCV) weighing not more than 20 tons, include a machine diameter of 1.0 meter and a length limit of 1.5 meters.

The polyphase multipole FTP machines require rectification of both the self-excitation current and the main gun output current requirements. Advanced SCRs

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14. ABSTRACT

Electric armaments of coilgun or railgun types require repeated bursts of extremely high power (gigawatts), considerable amounts of energy (tens of megajoules), delivered in several milliseconds. Compensated pulsed alternators, due to their high power and energy densities, have emerged as leading candidates for power supplies for railguns of the future. This paper examines test results of completed cornpulsator-based systems such as the Cannon Caliber Electromagnetic Launcher, with the objective of formulating estimates of upper bounds to the delivered energy density achievable by rotating electrical machines designed to meet the power requirements of electromagnetic guns. The effects of increasing rotational speeds (for increased energy storage and higher voltage) and of increasing allowable composite material strength and temperature levels on armature-excitation mutual inductances is considered in scaling up machines for application to tank main armament requirements.

15. SUBJECT TERMS

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and triggered vacuum switches (TVS) [6] are currently promising "near-term" candidates for the rectification function, but this area is another major technological challenge for the EMG program. It will not be addressed here. For rough estimates, about 150 kg per MJ breech DED is optimistic.

B. Approach

Each section below addresses a specific technical area. After brief discussion of the objective and constraints, appropriate equations are formulated to provide the output parameters needed to describe the performance of the coupled railgun and compulsator. The equations are then "wired" together in a spreadsheet format so that any input can be individually changed and the changes in the ensemble of outputs observed. The objective is to obtain an output ensemble that approaches an optimum while complying with selected constraints. Inputs are component dimensions, densities, rotational speed, specific heat, resistivity, etc. Outputs are machine diameter and length, stress level in the rotor support banding, rotor stored energy, launch package acceleration, velocity and energy; temperature rise, and other measures of performance.

The analysis is for a four-pole, four-phase machine. Two poles will not produce a high enough frequency, and terms associated with reduction of machine internal impedance approach unity much more rapidly with increasing pole pair numbers. Four-phase windings utilize winding volume efficiently.

II. LAUNCH PACKAGE EQUATIONS OF MOTION

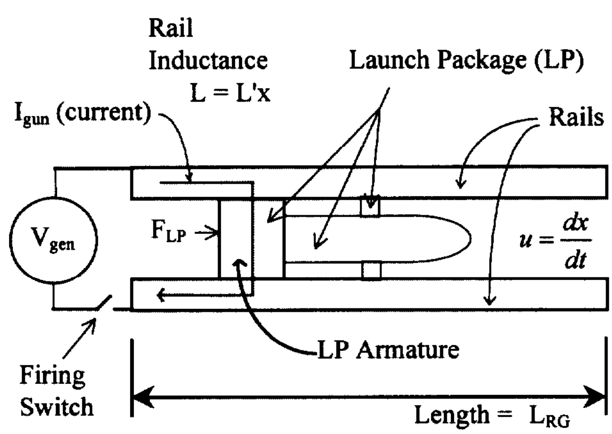

Figure 1. Railgun Diagram.

The impressed voltage V is given by

$$V = d(IL)/dt + IR \quad \text{V} \qquad (1)$$

$$= d(dL/dx)(dx/dt) + L(dI/dt) + IR \quad \text{V} \qquad (2)$$

Electric Power (P_{el}) is:

$$P_{el} = VI = I^2L'u + IL(dI/dt) + I^2R \quad \text{W} \qquad (3)$$

Power into the LP is $I^2L'u$, $IL'u$ is the back emf. We can also write electromechanical power:

$$P_{em} = d(LI^2/2)dt + d(mu^2/2)/dt + I^2R \quad \text{W} \qquad (4)$$

$$= I^2Lu/2 + LI(dI/dt) + mu\dot{u} + I^2R \quad \text{W} \qquad (5)$$

$P_{em} = P_{el}$, so

$$I^2L'/2 = m\dot{u} = F_{LP} \quad \text{N} \qquad (6)$$

For the gun current, we can write:

$$I_g = (V_{gen} - uL'I_g)/X_s \quad \text{A} \qquad (7)$$

where $uL'I_g$ is the back emf and X_s is the system reactance, which will be discussed in Section IV in connection with compensation. Solving for I_g,

$$I_g = V_{gen}/X_s(1+ u/u_{ref}) \quad \text{A} \qquad (8)$$

$$F/m = \dot{u} = V_{gen}^2 / 2mX_s^2(1+u/u_{ref})^2 \quad \text{m/s}^2 \qquad (9)$$

$$= \dot{u}_\circ / (1+ u/u_{ref})^2 \quad \text{m/s}^2 \qquad (10)$$

$$\dot{u} = u_{ref} / T_\circ (1+ u/u_{ref})^2 \quad \text{m/s}^2 \qquad (11)$$

where $T_\circ = u_{ref} / \dot{u}_\circ$ and $u_{ref} = X_s / L'$.

V_{gen} and hence $\dot{u}_\circ$ is not constant, but decreases as the back emf rises due to LP motion. If it is treated as constant, as it is to allow a simple closed form solution for the LP velocity and displacement, then the effect of the back emf is reduced to a term multiplying the transient reactance. This reduced effect of the back emf causes the calculated gun current to be higher than in the actual gun, but is valid as an upper bound estimate of performance. With constant $\dot{u}_\circ$, the integrals are:

velocity $u = u_{ref}[(3t / T_\circ + 1)^{1/3} - 1]$ m/s (12)

displacement $x = u_{ref}T_\circ [(3t/T_\circ + 1)^{4/3} / 4 - t/T_\circ - 1/4]$ m (13)

acceleration $\dot{u} = u_{ref} (3t / T_\circ + 1)^{-2/3} / T_\circ$ m/s² (14)

by differentiation of u.

The motion of the launch package (acceleration, velocity, and position) is depicted in Fig. 2 below. The lighter two-shot compulsator (temperature limited) has low average to peak acceleration ratio (piezometric ratio), compared to the heavier eight-shot machine. The low ratio translates to a high parasitic mass in the LP, substantially reducing payload effectiveness. The model

prediction is unrealistic, however, since an actual current profile has to start from zero as shown in Fig. 3.

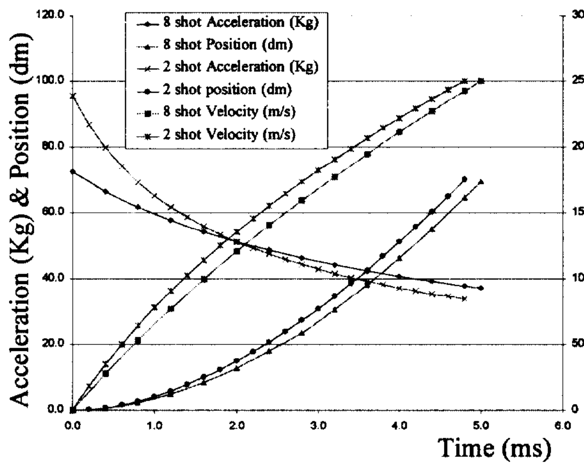

Figure 2. Launch Package Motion.

Note the shape of the actual gun current that produces this motion, shown in Fig. 3. This current profile also has a low piezometric ratio because of the low current in the second half of the profile, which would be more obvious if the current squared (proportional to acceleration) were shown.

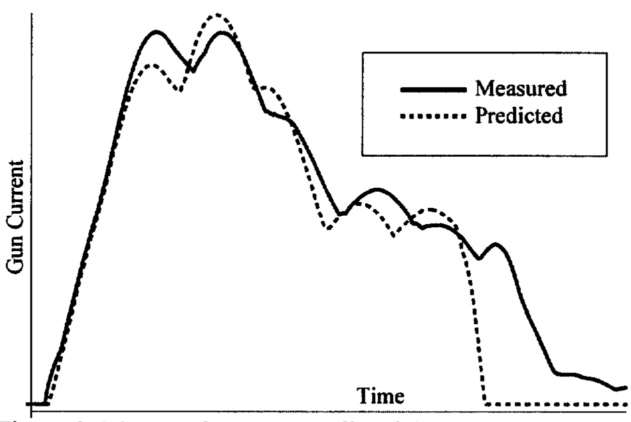

Figure 3. Measured Versus Predicted Gun Current.

III. ROTOR COMPONENTS

Displayed in Fig. 4 below are the principal components of the rotor:

Armature windings	r: radius of:
Field windings	r rotor
Rotor banding material	f field
Environmental screen	a armature
Composite support structures	b banding
	m machine
	x screen

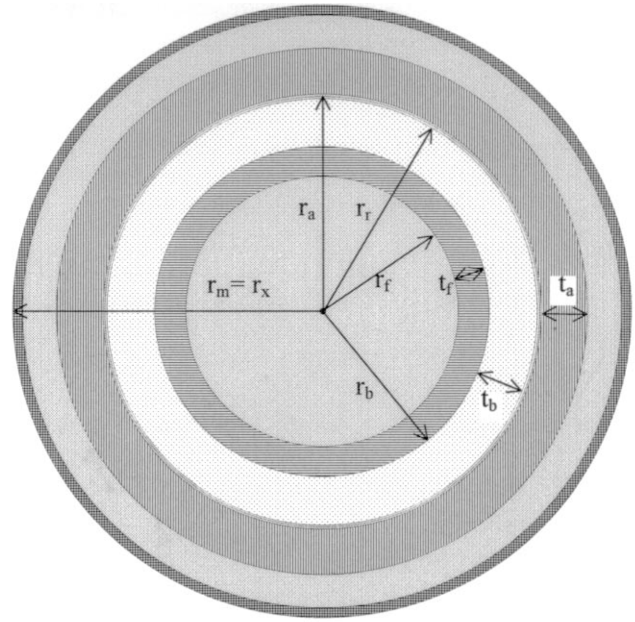

Figure 4. Machine Cross Section.

A. Banding Stress

All the hoop stress is assumed taken by the composite banding. The banding stress includes that due to its own density, plus that due to an apparent increase in density due to the field conductor mass loading. The total tension stress per unit cross section of the banding is:

$$S = (\Delta T_f + \Delta T_b)/ t_b \Delta z \qquad (15)$$

where Δz is the axial increment.

$$= \omega^2 (r_b+t_b/2)^2 \rho_b [(r_f+t_f/2)^2 \rho_f t_f / (r_b+t_b/2)^2 \rho_b t_b + 1] \qquad (16)$$

$$= \omega^2 (r_b+t_b/2)^2 \rho_b (k + 1) \quad \text{ksi} \qquad (17)$$

where the "payload factor" is

$$k = (r_f + t_f/2)^2 \rho_f t_f / (r_b+t_b/2)^2 \rho_b t_b \qquad (18)$$

Note that k decreases as t_b increases, reducing the stress.

B. Banding Preload

In the absence of a capability to support a substantial radial stress, circumferential banding stress at constant rotational speed increases with the square of the radius. In an isolated rotating cylindrical banding shell, doubling the radius quadruples the strain. Outer rings tend to lift off inner rings. Thus a substantial tension preload is required in outer layers to avoid interlaminar shear failure during high shear stress events, such as gun discharge. There are ways to reduce this effect, such as strain matching in inner layers, but the consequence of this

situation is that the full tensile strength of the banding may well not be useable, (as determined by detailed finite element analysis) and certainly the amount of preload subtracts from the available stress margin. Also, the assembly of the banding rings with interference fit to obtain high preloads is historically very difficult. In this analysis, this problem is recognized by increasing the calculated stress by 25% to account for the preload, and assuming that some degree of strain matching is achieved if more than about half of the tensile strength is used.

IV. THERMAL MANAGEMENT

Size (and hence mass) of the conductors is determined by the allowable temperature rise per discharge, or for a specified series of discharges in a fixed time interval. Because the rotor and stator conductors are imbedded in the composite support structures, and there is a significant performance penalty for adding anything which increases the spacing between the rotor and stator windings, the use of active cooling is probably not feasible. Further, the stator conductors must be made with Litz (stranded) wire to avoid excessive eddy current losses, so even if coolant passages were provided, the prompt cooling needed between discharges would be prevented by poor thermal conductivity. Thus the approach taken here is to design the conductors to be heat sinks and limit the number of discharges (shots) by the allowable temperature rise for the composite structure.

We need expressions for the heating of the field windings for the self-excitation (charging) phase and the discharge phase immediately following. (The field current increase due to the armature reaction and the current during the post-discharge decay are ignored.) The "bootstrap" process [2] consists of injecting a "seed" current from a (large) capacitor into the field winding which is connected to a full-wave rectifier driven by the armature winding. The field current increases exponentially with a time constant given by:

$$t_c = L_f/(cG + R_f) \qquad \text{s} \qquad (19)$$

where L_f is the field coil inductance, G is the phase voltage per field ampere, c is the number of equal parallel-connected field coils squared, to reduce the time constant, and R_f is the field resistance [2]. This may require revision based on ref. [2].

The field charging current I_f is thus:

$$I_f = I_{of} e^{t/t_c} \qquad \text{A} \qquad (20)$$

where I_{of} is the initial capacitor-provided seed current.

The field current rms current density during charging is:

$$J_{f\,rms} = I_{f\,rms} / A_{fc} = I_{of}[\,(t_c(e^{2t_{ch}/t_c} - 1)/2t_{ch})^{1/2}]/A_{fc} \quad \text{A/m}^2 \quad (21)$$

where A_{fc} is the field conductor cross-sectional area, t_{ch} is the charging time to field current I_f, and I_{of} is the seed current.

The temperature rise $\Delta T_{ch\,f}$ for the charging pulse is:

$$\Delta T_{ch\,f} = rJ^2_{fc\,rms} t_{ch} / \rho s \qquad ^\circ\text{C} \qquad (22)$$

where r is resistivity (3×10^{-8} Ω-m), ρ is the density of aluminum (2720 kg/m^3), and s is the specific heat of aluminum (950 Joules / °C-kg).

The temperature rise due to the (assumed constant) field current heating during the gun discharge is:

$$\Delta T_{fd} = rJ^2_{fc\,rms} t_l / \rho s \qquad ^\circ\text{C} \qquad (23)$$

where t_l is the launch time. The field current drops rapidly after t_l and this contribution is ignored. The total ΔT_f is thus:

$$\Delta T_f = r(J^2_{fc\,rms} t_{ch} + J^2_{fc\,rms} t_l)/\rho s \qquad ^\circ\text{C} \qquad (24)$$

For the armature heating estimate, we take phase voltage divided by the transient reactance [11] to get phase current, assumed sinusoidal, divide by $\sqrt{2}$ for rms current, then apply the time dependent back emf using the solution for u for the time dependence of the phase current rms amplitude. The result for the rms phase current density is:

$$J_{a\,rms} = (V_{ph}/\sqrt{2}\,X_{ph} A_{ac})((t_c/t_{ch})(((3t_l/T_\circ)+1)^{1/3} - 1))^{1/2} \qquad (25)$$

where A_{ac} is the effective cross section of the armature conductors. The temperature rise for each phase is:

$$\Delta T_a = rJ^2_{a\,rms} t_l / \rho s \qquad ^\circ\text{C} \qquad (26)$$

The transient reactance is the synchronous (steady state) reactance reduced by the near-short-circuit armature reaction during discharge. Its effect is to increase substantially the phase current during the discharge phase. In this model there are two sources. One is the field coil, the other the environmental shield. Reference [7] argues for a compensation winding on the quadrature (interpole) axis of the rotor. The additional mass and banding support here would significantly reduce performance. The transient reactance is taken from Bumby [11]:

$$X_{ph} = 5.19\text{x}10^{-6} \omega l_i (1-(r_f/r_a)^4)(1-(r_a/r_x)^4)/(1-(r_f/r_x)^4)\,\Omega \qquad (27)$$

after inserting numerical values for the constants, and where ω is the machine rotational speed in radians/sec, and l_i is the effective length of the phase coil winding. The system reactance is from addition of all the sinusoidal phase currents to obtain the rms value of the gun current, and is the transient reactance divided by 2.56. As stated above in Section II, this overestimates the gun current.

The peak phase voltage is also taken from Bumby [11]:

$$V_{gen} = 5.45x10^{-7}\omega l_v T_f (r_f/r_a)^3(1-(r_f/r_x)^4 I_f/r_f \quad \text{V} \quad (28)$$

where numerical values of constants have been inserted, and l_v is the coil length for voltage generation, and T_f is the number of field turns in series and I_f is the field coil excitation current. This completes the equations which are combined in a spreadsheet format to obtain the desired outputs.

V. RESULTS AND CONCLUSIONS

The imposition of constraints on allowable banding stress level, minimum rotor energy storage, conductor temperature rise levels and/or number of shots without a cooling period, minimum LP velocity/kinetic energy values, system diameter and length, system weight all determine whether a solution can be found. The process starts with an estimate (or better, a prior calculation shown to converge on an acceptable solution) and by trial and error attempt to establish convergence on a local optimum. In non-convergence cases, the mass typically "runs away" when one is trying to keep stress and temperature under limits as well as meeting LP energy and other requirements.

This analysis indicates that a critical parameter is temperature rise per shot, as shown in Fig. 5:

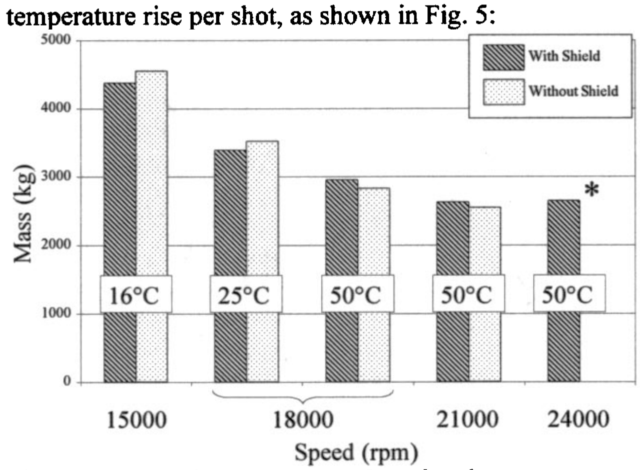

Figure 5. Compulsator Mass vs. Speed and AllowableTemperature Rise. (* banding stress 285 ksi, others about 250 ksi)

Convergence on a minimum weight solution with a banding stress limit cannot be obtained without a 25°C or even a 50°C rise. The conductor volume needs to be kept as small as possible to get the tight coupling necessary for maximum performance. This means current densities of $6\text{-}7x10^5$ A/cm^2.

Ref. [10] describes extensive work on RS-14A cyanate ester resin composites, which can operate with high strength in excess of 250°C. The use of the composite as a long time constant heat sink, not considered in the present analysis (by increasing the effective specific heat, for example) can expand the operating envelope for considerably more compact compulsators than appear feasible with epoxy resins.

It should be noted that even with large reductions in the weight of the rectifier switches from current state of the art, the weight of the gun, compulsator, and switch gear will exceed ten metric tons for tank armament for a twenty-ton Future Combat Vehicle, even with significant technological advances.

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